Policy instruments to fight against seawater intrusion in coastal aquifers: an overview

G.A. Giordana, M. Montginoul

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POLICY INSTRUMENTS TO FIGHT AGAINST SEAWATER INTRUSION IN COASTAL AQUIFERS: AN OVERVIEW

G. GIORDANA [1], *M. MONTGINOUL* [2]

[1] *Cemagref, UMR G-EAU and University of Montpellier I, UMR Lameta, Montpellier, France,*
[2] *Cemagref, UMR G-EAU, Montpellier, France*
giordana@lameta.univ-montp1.fr

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ABSTRACT. – Groundwater is a subject of rising social concern, especially in coastal zones where it is increasingly mobilized to satisfy water demands (essentially for agriculture and urban uses). Overexploitation of coastal aquifers may lead to permanent water quality degradation as a consequence of seawater intrusion. Policy measures have been undertaken in some countries either to avoid this threat or to solve the observed seawater intrusion. This article analyses, from an economic perspective, the different types of "policy instruments" taken in different empirical cases. It begins by the description of the theoretical framework detailing in particular the different elements entering in water management procedure (the resource, the agents and the regulator) and the different types of instruments that can in theory be implemented. Based on this theoretical framework, the different instruments mobilized in practice are presented. Finally, we conclude on the possible evolution of groundwater policy aimed to prevent and manage seawater intrusion in coastal aquifers.

Introduction

Groundwater is a subject of rising social concern, especially in coastal zones where most big cities are located. Due to growing demographic pressure in coastal areas, groundwater is increasingly mobilized to satisfy water demands (essentially for agriculture and urban uses). Overexploitation of coastal aquifers may lead to permanent water quality degradation as a consequence of seawater intrusion (Oude Essink 2001a). Policy measures have been undertaken in some countries either to avoid this threat or to solve the experienced seawater intrusion (Scheidleder *et al.* 1999). Likewise, many other countries face the overall challenge of changing groundwater policy to address the emerging problems (Livingston & Garrido 2004).

Groundwater is a complex resource to manage. On one hand, it is highly complicate to assess economic efficiency of a policy because few commodities are as pervasively involved in human economic activities as water is. On the other hand, groundwater management tends to lag behind the development of geophysical and geochemical knowledge, as the aquifers' characteristics determine withdrawals' impact on the resource state and the way these impacts spread on the economic system. Additionally, groundwater is a substitute of surface water (open bodies of water such as streams or lakes); then, an integrated management is almost unavoidable.

As a consequence, public policy may take a variety of forms, which will be further called "policy instruments": *regulations* (to restrict withdrawals), *pricing and trading* (to incite to reach economic efficiency), and *public investments* (to artificially recharge groundwater or to provide substitutable water resources). These public policies can be roughly classified into two broad groups (which can be combined in practice): *demand-side* and *supply-side* policies. The former refers to every measure taken to reduce or limit withdrawals, while the later aims to prevent water resource degradation without restricting water consumption.

Some questions arise about the direction that public interventions will take when coastal aquifers must be managed: how important will be the public investment in groundwater policy? Will regulation aim to reduce withdrawals put forward into policy? What will be the weight of economic incentives (pricing, penalties, etc.) in these regulations?

This article aims at contributing to answer these questions by analyzing policy instruments taken in different empirical cases. It first describes the theoretical framework detailing in particular the instruments that can in theory be implemented. Then, policy instruments mobilized in practice are presented. Finally, we conclude on the possible evolution of groundwater policy aimed to prevent and manage seawater intrusion in coastal aquifers.

Seawater intrusion management: analysis framework

Seawater intrusion occurs when the natural groundwater flow is inverted due to withdrawals which reduce the freshwater head of a coastal aquifer having sea connections (Oude Essink 2001a). These phenomena may be continuous (in time and space), producing a gradual degradation of chemical characteristics of freshwater (Cummings 1971), or discrete (in time) as freshwater head declines below some threshold level abruptly rendering the aquifer (or some wells) useless (Tsur & Zemel 1995). In this last case, there may be a lag between the withdrawal and its impact on freshwater quality. Moreover, seawater intrusion can be reversible or irreversible as the cost of restoring the aquifer is affordable or prohibitively large (Tsur & Zemel 2004). Continuity and reversibility features depend on three main characteristics: the relative level of aquifer with respect to sea level, the total groundwater recharge (essentially precipitations net from withdrawals), and the aquifer's size and type (geological and hydrological characteristics, in particular the hydraulic conductivity) (Petit 1996).

From a theoretical point of view, seawater intrusion occurs because property rights on groundwater (as every common-pool resources - CPR) are ill-defined. Groundwater is then overexploited, phenomenon known as the "tragedy of the commons" (Hardin 1968). In this situation, four types of negative externalities prevent market to allocate the resource efficiently: (i) a *stock externality*, when current extractions reduce future withdrawal possibilities (Provencher 1995); (ii) a *pump cost externality*, when current withdrawals by reducing the water head increase the (current and future) pumping cost (Provencher 1995); (iii) a *risk externality*, when groundwater represents an insurance when surface water flow is stochastic (Provencher & Burt 1993); (iv) a *water quality externality*, when the level of groundwater stock has an impact (which can be negative or positive) on water quality (Roseta-Palma 2002, Roseta-Palma 2003), as for seawater intrusion in coastal aquifers. Whilst *stock* and *pump cost externalities* are also current in the exploitation of other renewable natural resources (fisheries, forest, and also biodiversity (Levhari *et al.* 1981, Levhari & Mirman 1980)), *risk* and *water quality externalities* are specific to groundwater exploitation.

In the neoclassical framework, the presence of externalities justifies public intervention to efficiently allocate resources. But, as initially stated by Gisser & Sanchez (1980), centralized groundwater demand management may not generate sufficient welfare gains to be worth enough [this recurrently empirical phenomenon is known as *Gisser-Sanchez effect* (GSE)]. However, theoretical and empirical attempts to address GSE robustness [see (Koundouri 2004a, Koundouri 2004b) for reviews] reveal that welfare gains of management may vary depending on hydrologic and economic parameters. Notably, the GSE is quite sensitive to the slope of demand function (Nieswiadomy 1985). This suggests that the presence of different kind of users enhance the benefits to manage groundwater demand. And it is the case in coastal areas where groundwater can be an input of agricultural or industrial goods, or just a final product that satisfies potable water needs of cities and individual households. Each water use can be characterized in terms of water quantity (and the demand sensitivity), required water quality, and access time.

The groundwater regulator is charged to balance water demand and water supply by implementing management tools prescribed in the legal framework. However, when it exists, the regulator is not a unique entity: there is a big institutional and legal complexity around groundwater management, which can affect the choice of policy instruments, their efficacy and their efficiency (e.g. the Algerian Agricultural Ministry subsidies tube wells while the Environment Ministry forbids them). Then, the interests of each institution governing groundwater exploitation have to be accounted for cautiously to understand policy choices (Dinar 2003). Different groups of users and non users (like environmentalists) try also to influence the choice of instruments. Then, policy cost distribution also matters as it is intimately linked to the political viability of alternative means to address the seawater intrusion problem.

A wide range of policies aimed to cope with environmental externalities has been developed in the economic literature (Baumol & Oates 1988, Brown 2000). In addition to these policy instruments, mainly built on rather simplistic assumptions, other management solutions exist to fight against seawater intrusion; we classify them in three groups, provided they act on groundwater supply, groundwater demand, or simultaneously on groundwater demand and supply.

Supply policies

Supply policies are implemented to alleviate the aquifer from anthropic pressures or to directly protect it from seawater intrusion.

They consist of different engineering solutions either to increase or to maintain groundwater availability. Supply policies can act directly on aquifer: groundwater may be artificially recharged (sedimentary aquifers), underground channels and water rooms can be built to increase the aquifer storability (chalk and hard rock aquifers), even underground concrete or water dams can be employed.

Supply policies can also consist of investing in water substitutes: surface water can be made available by river dams (and distributed by channel or pipeline networks) or aqueducts; other water substitutes are found through seawater desalinization and waste water reuse.

These forms of investment find a wide political approval, especially because they are often initially subsidized (Garrido 1999). However, attention must be paid to avoid distorted signals for the long run (dynamic efficiency). Prices should be set at a correct level to allow users to take into account the real cost of water and to economically and financially justify the development of additional supplies (Dinar 2003).

Demand policies

Several instruments can be mobilized to manage groundwater withdrawals. We call *economic* instruments those advocated principally by economists, namely water pricing, water markets, collective penalties, etc., and *command and control* instruments those regulations imposed by governmental agencies like volume quotas, design standards on the tube wells' number, restrictions on the drilling depth, etc. Finally, it is sometimes difficult to observe the level of groundwater extraction, obliging to implement incentive contracts that reveal the real behavior of withdrawers. Let's now present in more details some of these demand-side instruments.

Water is priced following a generic function (Montginoul 2006): $B = aX + b$, with B, the total bill, X the water consumption level (in m^3), a the price per unit of water used; b the fixed part. The proportional part (a) can be either constant whatever water consumption level or priced "per block" (increasing or declining with the consumption level). Water pricing plays two key roles, an economic, as it signals water scarcity value and opportunity cost to guide allocation decisions, and a financial one, as it represents the main cost recovery mechanism. Moreover, it is the lonely instrument which can serve to fund infrastructure investments (aquifer recharge, etc.). Different pricing systems can be implemented, depending on the information available to the regulator and political constraints. In practice, water pricing is often set only to cover supply costs. And it explains the most commonly adopted structure (a weak "*a*" and a high "*b*") following water cost structure. However, water pricing suffers some drawbacks that may reduce its chances to be implemented in practice, in particular when there is no cost to recover (in this case it is not a price but a tax). Notably, it requires information on individual water consumption (knowing all groundwater users and equip them with water meters). Finally, a price imposes a financial burden on withdrawers and its impact on total groundwater withdrawals depends on its capacity to encourage extraction reductions.

The quota imposes an upper limit to water consumption and can be specified using volumetric, discharge or time units (eventually combined) (Montginoul 1998). In general, quotas are accompanied of technology standards (on the depth and the location of boreholes, on the type of pumping material, etc.). Usually, certainty on environmental effects of a policy is preferred to a potential effect that may have a great distributional impact. Then, regulator prefers *command and control* instruments to manage groundwater withdrawals rather than economic instruments: the quota directly constraints users instead of indirectly modify their behavior through market signals (Bohm & Russell 1985).

However economic literature criticizes quota for its rigidity (Baumol & Oates 1988), even if it can be calculated to produce the same result than an efficient pricing and if nothing lets to conclude that a publicly settled pricing could be easier to modify. While quota demands similar monitoring efforts than a price, its main drawback comes from the poor incentives it gives to a technological change (no dynamically efficient). This handicap can be nevertheless overstepped if individual transferable quotas (ITQ) are created. These quotas, treated as water rights, can be exchanged in water markets when the initial allocation does not guarantee efficiency or when some conditions have exogenously changed (new demand, supply modification, etc.).

Another instrument, the "ambient tax", is proposed by economic literature to solve diffuse pollution problems and can be adapted to manage groundwater, when individual withdrawals can not be observed (Segerson 1988, Shortle & Horan 2001). Ambient tax is designed from an observed variable (for example the groundwater level) which is affected by individual but not observable decisions (here the withdrawals). This tax is billed to all users (withdrawers) if the observed variable reaches a threshold which was decided to not overpass. Although an efficient "ambient tax" does not require knowing individual withdrawals (as for pricing and quotas instruments), it also requires a high level of information because users' demand functions have to be known to be able to efficiently design the ambient tax level. Moreover, its political acceptability may be quite limited, provided the implicit unfairness it breeds; notably, a withdrawer who exploits efficiently groundwater may be charged due to the non compliance with the environmental goal of someone else.

Supply/demand policies

As advances in geophysical, geochemical and hydrogeological knowledge allow to better understand the impact of withdrawals on groundwater resource (and then to better assessing related externalities), some fine tune policies become available. For example, it is the case of a regulation trying to optimally localize tube wells taking into account coastal aquifer's characteristics (in particular by keeping them away from the sea); it is also the case of a policy aiming to spread withdrawals within the year. This kind of policies are, evidently, more efficient since they are based on a system precisely defined enabling to intervene, at the same time, on different dimensions of the problem; namely, time and spatial dimensions.

To conclude, the analysis framework advanced to analyze and compare on a homogenous basis diverse empirical cases consider several elements: the aquifer, the regulator, the groundwater demands, and the policy instruments. Based on this analysis framework, different seawater intrusion management experiences were reviewed and are presented in the next part (Table I).

Table I. – Literature material mobilized for the presentation of the different cases.

Studied Cases	References
Albania	Cesti R, Klees R *et al*. 2003. Water Resources Management in South Eastern Europe (Volume 1). Washington, World Bank: 65 p.
	Eftimi R. 2003. Some considerations on seawater-freshwater relationship in Albanian coastal area. Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos, Madrid, Instituto Geológico y Minero de España.
	Silveira MP, Masson C *et al*. 2001. Environmental Performance Review for Albania, United Nations Economic Commission for Europe, Economic Commission for Europe: 169. Ch. 1, 2 et 6.
Algeria	Djabri L, Hani A *et al*. 2003. L Algérie, un pays en voie de développement, a-t-elle déjà développé un biseau salé ? Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos, Madrid, Instituto Geológico y Minero de España.
California (general)	California s Groundwater – Bulletin 118, Update 2003. Department of Water Resources, State of California, ch. 1, 2, 5 and supplemental report.
	Department of Water Resources. State of California. www.water.ca.gov
	Garrido A 1999. Tarification de l eau à usage agricole dans les pays de l OCDE. Paris, Organisation de Coopération et de Développement Economiques, Direction de l Environnement: 62 p.
	Howe CW 2002. Policy Issues and Institutional Impediments in the Management of Groundwater: Lessons from Case Studies. *Environment and Development Economics* 7(4): 625-41.
	Loaiciga HA, Leipnik RB 2001. Theory of sustainable groundwater management: an urban case study. *Urban Water* 3(3): 217-28.
	Narasimhan TN, Kretsinger V 2003. Developing, managing, and sustaining California s groundwater resources. Los Angeles, Groundwater Resources Association of California: 26 p.
	Ostrom E 2000. Collective Action and the Evolution of Social Norms. *Journal of Economic Perspectives* 14(3): 137-158. Chapter 13.
California (the Orange case)	California s Groundwater – Bulletin 118, Update 2003. Department of Water Resources, State of California, ch. 2 and Coastal Plain of Orange County Groundwater Basin information.
	Orange County Water District. Historic information. www.ocwd.com
	Département des ressources en eau, Etat de Californie. www.water.ca.gov
	Ostrom E 2000. Collective Action and the Evolution of Social Norms. *Journal of Economic Perspectives* 14(3): 137-158. Chapter 13.
Croatia	Biondic B, Biondic R 2003. State of Seawater Intrusion of the Croatian Coast. Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos, Madrid, Instituto Geológico y Minero de España.
	Cesti R, Klees R *et al*. 2003. Water Resources Management in South Eastern Europe (Volume 1). Washington, World Bank: 65 p.
	Chohin-Kuper A, Rieu T *et al*. 2002. Les outils économiques pour la gestion de la demande en eau en Méditerranée. Cemagref: 34 p.
England	Robins NS, Jones HK *et al*. 1999. An Aquifer Management Case Study – The Chalk of the English South Downs. *Water Resources Management* 13(3): 205-218.
	Site Internet du "Department of Environment, Food and Rural Affairs", www.defra.gov.uk
	Garrido A 1999. Tarification de l eau à usage agricole dans les pays de l OCDE. Paris, Organisation de Coopération et de Développement Economiques, Direction de l Environnement: 62 p.
European Union	Henocque Y, Andral B 2003. The French approach to managing water resources in the mediterranean and the new European Water Framework Directive. *Marine Pollution Bulletin* 47(1-6): 155-61.
	Kallis G, Butler D 2001. The EU water framework directive: measures and implications. *Water Policy* 3(2): 125-42.
	Scheidleder A, Grath J et al. 1999. Groundwater quality and quantity in Europe. Copenhagen, European Environment Agency

Policy instruments to fight against seawater intrusion in practice

It is out of the scope of the paper to review all studies carried out on seawater intrusion management in coastal aquifers. We restricted the number of empirical cases to those we have found enough and fair information, and that match some specific characteristics. More precisely, we concentrate our bibliographic research on empirical cases concerning multi-layer sedimentary coastal aquifers that suffer from seawater intrusion as a consequence of overexploitation; cases with chalk aquifers are considered as well. Other dimensions that guided our choice were the presence of many water uses (agricultural and drinking water distribution) and a seasonality of withdrawals.

Even if many cases present a variety of coastal aquifer types, we roughly classify them into two categories: alluvial and chalk aquifers cases (Table II). Some of the cases enter in both categories (Albania, Italy and Spain, as many local aquifers were considered in the bibliographic review), or in any category at all (Algeria because its reservoirs are constituted of sand). The main common characteristic between cases is a coastal aquifer's overexploitation (revealed in particular by a water head decline and sometimes also by a seawater intrusion). In each category, seawater intrusion shows different degrees of reversibility, and can be more or less widespread; it can take place only during the summer season (Albania, Croatia, England, Greece) when water demand is at its higher level and recharge at its lowest, or it can stay structurally (California, Spain, Algeria, France, some basins of Italy, Turkey). The consequences of seawater intrusion

Table I. – (Continued)

Studied Cases	References
France	Agence de l Eau Rhône-Méditerranée Corse, Bureau de Recherches Géologiques et Minières (BRGM), Chambre d Agriculture 66 (CDA 66), Conseil Général des Pyrénées-Orientales (CG 66), Direction Départementale de l Agriculture et de la Forêt (DDAF), Direction Départementale des Affaires Sanitaires et Sociales (DDASS) et Direction Régionale de l Environnement (DIREN) (2003). Connaissance des eaux souterraines de la plaine du Roussillon, Perpignan. Etat des lieux, Décembre. 47 p.
	Bouleau G 2003. Acteurs et circuits financiers de l eau en France. Montpellier. Ec. Nat. Génie Rural Eaux Forêts, report. 92 p.
	Chohin-Kuper A, Rieu T *et al*. 2002. Les outils économiques pour la gestion de la demande en eau en Méditerranée. Cemagrefr: 34 p.
	Dörfliger N (2003). Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos, Madrid, Instituto Geológico y Minero de España.
	Garin P, Loubier S *et al*. 2001. Les Associations Syndicales Autorisées: bilan d étude sur leur fonctionnement et leurs stratégies de maintenance. Montpellier, Cemagref: 57 p.
	Garrido, A. (1999). Tarification de l eau à usage agricole dans les pays de l OCDE. Paris, Organisation de Coopération et de Développement Economiques, Direction de l Environnement: 62p.
	Ledoux and Crozet 2001. Gestion équilibrée de l eau et gestion de l espace. Guide juridique et pratique pour les interventions publiques sur terrains privés. Montpellier. Rapport Direction Régionale de l Environnement. 225 p.
	Nixon S, Trent Z *et al*. 2003. Europe s water: An indicator-based assessment. Copenhagen, European Environment Agency: 97 p.
	Petit V 1996. Les aquifères littoraux de France métropolitaine, BRGM: 119 p.
	http://www.cieau.com
Greece	Chohin-Kuper A, Rieu T *et al*. 2002. Les outils économiques pour la gestion de la demande en eau en Méditerranée. Cemagref: 34 p.
	Garrido A 1999. Tarification de l eau à usage agricole dans les pays de l OCDE. Paris, Organisation de Coopération et de Développement Economiques, Direction de l Environnement: 62 p.
	Herrington MP 1999. Tarification de l Eau à Usage Ménager dans les pays de l OCDE. Paris: 80 p.
	Karavitis CA 1998. Drought and urban water supplies: the case of metropolitan Athens. *Water Policy* 1(5): 505-524.
	Lambrakis N, Marinos P (2003). The salinisation of coastal aquifers in Greece: a general review. Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos, Madrid, Instituto Geológico y Minero de España.
	Manoli E, Assimacopoulos D *et al*. 2004. Water supply management approaches using US on the island of Rhodes, Greece. *Desalination* 161(2): 179-189.
Italy	Barrocu G 2003. Seawater intrusion in coastal aquifers of Italy. Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos, Madrid, Instituto Geológico y Minero de España.
	Sappa G, Vitale S 2002. Groundwater protection: contribution from Italian experience. Department of Hydraulics, Transportations and Roads – University "La Sapienza" of Rome.
Spain	Gómez Gómez JD, López Geta JA *et al*. 2003. The State of Seawater Intrusion in Spain. Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos, Madrid, Instituto Geológico y Minero de España.
	Gómez Gómez JD, López Geta JA *et al*. 2002. Aquíferos costeros de Málaga. Homenaje a Manuel del Valle Cardenetes, Instituto Geologico y Minero de Espana, Confederasion Hidrografica del Guadalquivir, Instituto del Agua de Andalucia (COPTJA), Diputacion Provincial de Grenada
	López Geta JA, Parra y Alfaro JL *et al*. 1988. Acuifero costero de Fuengirola (Malaga). Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos, Madrid, Instituto Geológico y Minero de España.
	Plan hydrologique du bassin Sud. Site internet de la Confédération Hydrologique du Sud www.chse.es
	Kent M, Newnham R *et al*. 2002. Tourism and sustainable water supply in Mallorca: a geographical analysis. *Applied Geography* 22(4): 351-374.
Turkey	Chohin-Kuper A, Rieu T *et al*. 2002. Les outils économiques pour la gestion de la demande en eau en Méditerranée. Cemagref: 34 p.
	Garrido A 1999. Tarification de l eau à usage agricole dans les pays de l OCDE. Paris, Organisation de Coopération et de Développement Economiques, Direction de l Environnement: 62 p.
	Günay G 2003. Seawater intrusion in coastal aquifers of the Mediterranean coast of Turkey. Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos, Madrid, Instituto Geológico y Minero de España.
	Herrington MP 1999. Tarification de l Eau à Usage Ménager dans les pays de l OCDE. Paris: 80 p.
	(2000). Water Resources Development in Turkey, Mediterranean Hydrological Cycle Observing System. 2004.

are positively related to the degree of reversibility: in the chalk category seawater intrusion obliges, sometimes, to retire polluted boreholes from exploitation for a while, but they are again operational after a rain season (the chalk of England South Downs or in Croatia); in some cases from the alluvial category, seawater intrusion has only a diffuse but long-lasting impact, leading to a lower groundwater quality, which can be still (at least partially) exploited (California, France, Spain).

Users' characteristics are also various but in all studied cases two types are systematically present and responsible for the main part of withdrawals: the agriculture and the urban water. Other users are also met: the tourism (in France, Italy, Spain, and Turkey), the industry (in Albany, Algeria, California, and Spain) and individual households – through private tube wells (like in the south of France). In all cases, withdrawals are mostly concentrated in summer.

Table II. – Implemented policy instruments and aquifer type.

	Aquifer type		Demand side					Supply side			
	Alluvium	Chalk	Pricing	Quotas	Permits	Financial penalties	Other regulations	Artificial recharge	Substitutes development	Water transfer	Others
Albania	x	x	x (foreseen)		x (foreseen)	x (foreseen)					
Algeria				x			x		x		
California (Orange County)	x		x		x		x	x	x	x	x
Croatia		x			x		x	x	x	x	x
England (Chalk of the English South Downs)		x	x	x	x		x		x	x	x
France (south of metropolitan)	x		x		x		x		x		
Greece		x					x		x		
Italy	x	x			x			x	x	x	x
Spain (Balearic Islands and *Fuengirola aquifer)*	x	x	x	x	x		x		x	x	
Turkey (Mediterranean region/Dörtyol-Erzin plain)	x			x	x		x	x			x

Agriculture was historically the biggest groundwater withdrawer. The urbanization of coastal areas limited afterwards the abundance of groundwater resources (like in California and the south of France). Other changes are also met: a coastal mass tourism (in Mediterranean countries), the installation of industries closed to urban areas (in Algeria), a change in irrigation practices (to abandon surface water for groundwater, like in Albania and some basins in the south of France).

The juridical groundwater status is various. Even if in some cases this status is not clearly defined (Albania, Algeria, Greece), three property regimes can be distinguished: common property (France, Turkey), private good (California, with a distinction between senior and junior rights), and local or national State property (Croatia, England, Italy, and Spain). In most of the studied cases, groundwater can be considered as a private good linked with land property. However, as groundwater is not systematically registered, users and withdrawals (other than urban water) are not known, excepting a few cases like the Orange case in California or the South of England.

The regulator capacity to deal with seawater intrusion is also highly various. Sometimes the legal framework doesn't exist or it is not adapted to solve the current management problems (Algeria, Greece, and Turkey). In other cases, governmental institutions have no clear responsibilities; they may also have opposite goals, or even have no funds to implement what they decide. It is for example the case in Albania where there is an innovative legislative framework but not enough financial resources to implement it.

Table II summarizes policy instruments that have been implemented. The key actions taken are on the supply side. The main action is the development of substitute resources: construction of rivers' dams (Algeria, California, Greece, Roussillon aquifer in South of France and Turkey), rainwater retention structures (California, Croatia and Spain), or aqueducts (California, Croatia, England and Italy) were the first actions performed. Non conventional substitutes like desalinization plants (Algeria, Greece, Italy and Spain) or waste water reuse (California, England, Greece, Italy, Spain and foreseen in Algeria) complement nowadays the choice of substitutable resources.

Direct actions to preserve coastal aquifers from seawater intrusion are also taken: artificial aquifer recharge (California, Croatia, Italy, and Turkey), construction of underground dams to stop seawater progression (California, Turkey) or of underground channels to increase storage capacity (Croatia, England). In the reviewed cases, studies on aquifer situation and its functioning are done only when these direct actions are foreseen.

The cases with an intensive use of supply policies [California, Croatia, England, Italy and Spain (Balearic Islands)] are those where there is an overall water resource deficit, or a spatial disparity on its availability. However, even if water has a high economic value, this is not sufficient to trigger heavy infrastructure investments: to invest, a concrete and current threat on the resource (which limits the local economic development) must occur. For instance, in the Orange County coastal plain (California) case, investments were done because the seawater intrusion progress threatened the regional economic sustainability (8% of the California State population) and because groundwater protection investments were the only way to ensure it: groundwater provides 75% of the global demand in this Orange plain; the rest is conveyed from other basins at a high cost, and taken from the Santa Ana River (that runs through the basin) which capacity is exhausted.

On the demand side management policies, permits are the most popular instrument. But anyone of the reviewed cases has developed a permit market. In general, permits precise the pre-required conditions of water extraction: they can specify the annual extraction, the instantaneous maximal flow, the water use and the water destination, the borehole's deepness and the pumping material's characteristics. Volume and flow meters can be also imposed (Spain, California, England, and France). When annual extraction is specified, the issued permit is more than an authorization to drill and pump but also a quota (Spain, England and Turkey). However, while permits allow knowing new extraction points and their characteristics, they won't remediate the ignorance on currently active but old boreholes; a probably costly census of users is needed (Albania, Algeria, Croatia, Greece, Italy, south of France).

Water pricing, to fight against seawater intrusion, is not the main demand-side instrument used due to its high informational conditions. Whilst these conditions are met for urban water and volumetric pricing is commonly implemented in most of the reviewed cases (California, Croatia, England, Italy, Spain), they are not met for the agricultural use. In this situation, the collective surface irrigation water price can have adverse effects: many users facing a surface water price increase (due to a reduction of subsidies on operational and capital cost of the irrigation channels) have shifted to individual groundwater irrigation as no charge exists on this resource (Albania and the Roussillon plain in South of France). However, some groundwater pricing policies are observed. Sometimes, they are applied to cover induced costs (like the aquifer recharge – for instance in Orange in California) and sometimes independently (California, England and France with Water Agencies' fees).

There are also other demand-side regulations that principally consist of: public education and awareness on water savings' practices (California, Greece, Balearic Islands, and Turkey), water wastes (Balearic Islands), and rationing (Algeria, Spain). And some fine tune policies are implemented in England (seasonally modify the location of withdrawals) and in Croatia (smoothing of withdrawals during the day). These both cases are characterized by chalk aquifers with a salinity concentration highly reactive to the groundwater flow variations.

Finally, in some cases, no policies are implemented to cope with seawater intrusion in particular, or with groundwater management in general. In Algeria, there is no clear legal framework, interpretation problems arise and responsibilities of the different regulators are not correctly defined: in this country, water management can be considered as a crisis management. In Albania, a modern legal framework exists, but it encounters many starting problems related to cultural and financial aspects.

Conclusion

This paper reviews policy instruments implemented in some empirical cases to fight against seawater intrusion in coastal aquifers. These instruments are classified into two broad groups (which may be combined): *demand-side* and *supply-side* policies.

The ignorance on demand characteristics is the main difficulty encountered to apply demand-side management. And the success of such policies critically depends on the means that the regulator disposes to design and to enforce them. For instance, the Balearic Islands (Spain) have already implemented demand-side instruments (pricing, quotas, permits and water saving education), but their persistent water deficit prevents them to expect an improvement of their already polluted aquifers.

That explains why demand policies are often implemented after supply management solutions: supply policies have sufficed to prevent seawater intrusion (Italy and France) or to limit its consequences (Croatia) until their realization becomes unfeasible (because no solution exists or supply actions are too expensive).

The most successful groundwater management experiences, California and England cases, are associated to a supply and demand side policies combination. While supply side policies allow to protect or increase available groundwater resources, demand side policies enables to fund them (pricing) and to dispose of accurate information about all relevant demand characteristics (volume, location, season, etc.). Consequently, the available information and the financial health of the management system results in a greater flexibility to adapt management to different scenarios. This flexibility is particularly precious once supply policies are no longer available, when resource reallocation is the only management option. However, a necessary condition to flexibility is a largely powerful regulator capable of correctly enforce policies (i.e. in the Orange County Water District, inspectors have the right to enter in private property to search boreholes).

This review shows also that groundwater pricing is not widely applied. And demand-side policies are successfully applied when groundwater management institutions are mature because they were early confronted to the seawater intrusion problem (also as the problem becomes a social concern withdrawers are less hostile to demand-side policies). The definition of the groundwater juridical status usually precedes demand-side policies, which are combined to supply actions. Then, sometimes they are aimed to assure the effectiveness (i.e. permits, quotas, seasonal restrictions, etc.) and/or durability (i.e. pricing to fund artificial recharge) of supply actions. But, they are not aimed to introduce economic incentives for reducing exploitation.

In conclusion, the most successful experiences are those whose investments were directly funded through groundwater pricing. In those cases, a virtuous circle in groundwater management (to fight against seawater intrusion) is generated. As correct pricing of the already developed resources allows the integration of supply augmentation with efficient demand management, it ensures the economic and financial justification for the development of additional supplies. However, even if in this paper cases have been roughly classified in successful and failed experiences, a more general analysis should consider them dynamically, as going through the different stages of a structural reform process.

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